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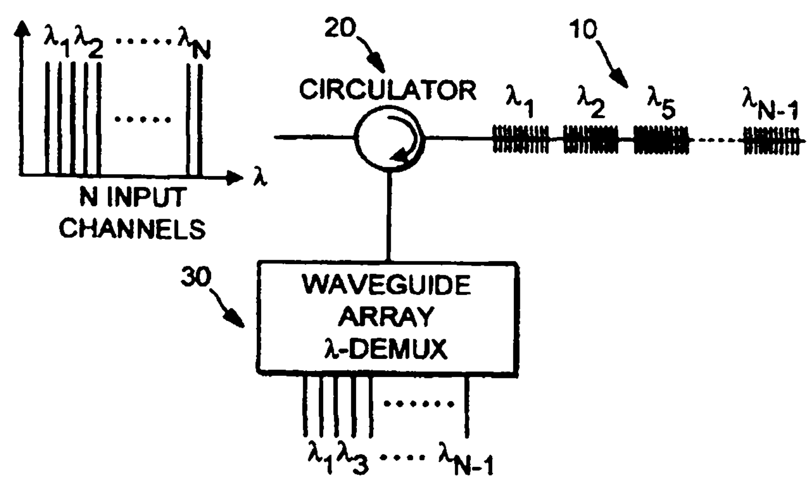
(54) Title: OPTICAL WAVELENGTH DIVISION MULTIPLEXER

(57) Abstract

An optical wavelength division demultiplexing apparatus for demultiplexing a multiplexed optical signal having a plurality of channels occupying respective wavelength bands. The apparatus comprising at least one waveband selector (10, 11) that acts to select wavelength bands corresponding to non-adjacent channels, the selected wavelength bands being routed to an associated array demultiplexer (30, 31) that outputs the selected wavelength bands as a parallel array of channels.



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OPTICAL WAVELENGTH DIVISION MULTIPLEXER

This invention relates to optical wavelength division demultiplexing apparatus and methods and to optical transmission systems including such apparatus.

There is an ever increasing demand for transmission capacity along optical fibre cable links such as telecommunication networks for applications such as the internet. The capacity of fibre links can be readily increased via wavelength division multiplexing (WDM). An example of a WDM system is shown in Y. Yano et al. (see publication references [1] and [2]). With wavelength division multiplexing the carrier beam is composed of several different wavelength bands, and information is added to each wavelength band. The fibre link transmits the beam containing the different wavelength band carriers, such that one fibre link can transmit a plurality of signals carrying separate information in what are termed channels. On receipt of the beam, it is demultiplexed into its separate wavelength bands or channels prior to the different signals being demodulated.

The channels are typically distributed evenly across a useable wavelength band of the fibre link. The wavelength band of the fibre link is limited by the available bandwidth of the erbium-doped fibre amplifier (EDFA); this in turn is defined by international specifications. The number of channels that can be transmitted via an optical fibre link is thus limited by the transmission bandwidth of the fibre link, the bandwidth of the channels themselves and their separation. A useful parameter defining the efficiency of bandwidth usage is the filling factor, F; this is given by the ratio of the channel bandwidth W, to the channel separation S, i.e.

$$F = W/S$$

so a higher filling factor implies more efficient use of the available bandwidth. One way to increase the filling factor is to reduce the channel separation. The separation is, however, limited by the efficiency of the multiplexer and demultiplexer. It is clearly easier to reproduce a signal from one channel, with reduced crosstalk from the other

channels, if the channels are widely separated. Reproducing a signal with reduced crosstalk from a channel that is close to its neighbours requires the use of a channel filter with a near rectangular shape.

Channel demultiplexing can be achieved using 1 x N WDM demultiplexers based on, for example, integrated concave grating WDM demultiplexers [3] or array gratings [4, 5, 6]. These devices provide parallel demultiplexing of the channels with approximately equal channel loss and channel spacing. The limitation of these devices is however that it is difficult to achieve near a rectangular filter shape so that a relatively large channel separation is required to prevent crosstalk. In reference [4], a value of F of 0.71 is quoted for a waveguide grating, although from the figures given it appears that a value of 0.55 may be more achievable in practice.

An alternative approach is the use of fibre gratings. Fibre gratings provide excellent filter shapes with controllable characteristics and low sidebands. There are however, several disadvantages associated with the use of such filters in demultiplexing. Fibre gratings are basically two port devices wherein light of different wavelengths is either reflected or transmitted. Thus in order to access the reflected channel they typically have to be used in conjunction with an optical circulator or coupler connected to the input port. To access many (N) channels i.e. for use as a demultiplexer, several configurations of fibre gratings have been proposed. In one, a 1 x N broad band splitter is employed to equally split the WDM signal into N approximately equal signals with the power of an individual channel being about 1/N of the input signal's power. Separate grating filters are then employed on each output leg to demultiplex the signal. This configuration is lossy, with an optical loss that is greater than 10 log N decibels. Other configurations have been proposed, but none is ideal as the grating is in essence a serial device. For example, if each grating were used in combination with a circulator and cascaded in series, then the first channel would suffer the loss equivalent to one circulator, ~ 1dB, whilst the N^{th} channel would suffer the loss of N circulators, ~ N dB.

In accordance with the present invention there is provided an optical wavelength division demultiplexing apparatus for demultiplexing a multiplexed optical signal having

a plurality of channels occupying respective wavelength bands, the apparatus comprising a wavelength band selector and an array demultiplexer connected to receive light from the wavelength band selector; the wavelength band selector being operable to select a plurality of wavelength bands corresponding to non-adjacent channels from the multiplexed optical signal; and the array demultiplexer being operable to demultiplex the wavelength bands received from the wavelength band selector to produce an array of output signals in parallel, each output signal representing a respective one of the channels of the multiplexed optical signal.

The device of the present invention alleviates the disadvantages of the prior art by providing an optical wavelength division demultiplexer that utilises a wavelength band selector (e.g. an arrangement of fibre gratings) that can be chosen for its filter characteristics in conjunction with an array demultiplexer that produces an array of output signals in parallel. A wavelength band selector that is operable to select non-adjacent channels from the multiplexed signal increases the separation between the bands that are sent to the array demultiplexer and thereby alleviates the crosstalk problems of this device. Thus the present invention can combine sharp and controllable filter characteristics of the wavelength band selector with the parallel advantage of the array demultiplexer.

Although the wavelength band selector may be arranged to transmit the selected plurality of wavelength bands a selector which reflects them is preferred. Many of the wavelength band selectors on the market which produce the best filter characteristics act to reflect the selected wavelength.

Although the device may be implemented using some fibre components, it is of course possible for other types of devices and waveguides to be employed. A particular example is the use of planar waveguide technology. For example, the whole demultiplexes could be embodied as a single integrated optical device.

Advantageously, the apparatus further comprises an optical circulator, the apparatus being arranged such that the wavelength band selector and the array demultiplexer are inter-connected via the optical circulator, a first port of the circulator being arranged to receive an optical signal, a second port being connected to a

wavelength band selector and a third port being connected to the waveguide array demultiplexer; wherein the circulator is operable to route the received optical signal to the wavelength band selector and to route the reflected plurality of selected wavelength bands to the array demultiplexer. This is a convenient way of allowing an essentially serial waveband selector to be used to produce a parallel array of channels.

In one embodiment, the wavelength band selector is operable to transmit remaining components of the input optical signal that have not been reflected, the transmitted signal containing wavelength bands corresponding to the channels that were not selected; the apparatus further comprising a second array demultiplexer connected to receive transmitted light from the waveband selector; the second array demultiplexer being operable to demultiplex the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the non-selected channels. This embodiment allows the demultiplexing of an extra set of channels with an extra array demultiplexer but without the need for an extra wavelength band selector. This is achieved by using the waveband selector to reflect the selected wavelength bands to one array demultiplexer and transmit the non-selected wavelength bands which correspond to other multiplexed channels to another array demultiplexer. Thus the device has a relatively low number of components and so can be economic to produce.

In preferred embodiments, the apparatus comprises N array demultiplexers and N wavelength band selectors, wherein N is an integer greater than 1; each of the N wavelength band selectors being operable to select a plurality of wavelength bands corresponding to non-adjacent channels from the multiplexed optical signal that, are different to the plurality of wavelength bands selected by the other N-1 wavelength band selectors; the apparatus being arranged such that the plurality of bands selected by each of the N wavelength band selectors are routed to a different one of the N array demultiplexers: the N array demultiplexers being operable to demultiplex the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the channels of the multiplexed optical signal. By having an apparatus with a plurality of wavelength band selectors and array

demultiplexers, the effective separation between channels supplied to each array demultiplexer can be made equal to several (e.g. N) channel widths.

In some embodiments, the N wavelength band selectors are connected in series and are operable to reflect the selected plurality of wavelength bands and to transmit remaining components of the optical signal. A series arrangement of the wavelength band selectors allows a plurality of wavelength band selectors to be used together without the need to split the input signal into separate signals. Splitting the input signal produces a plurality of signals of significantly reduced power compared to the original signal.

Advantageously, the apparatus further comprises an N+1th array demultiplexer connected to receive transmitted light from the Nth waveband selector containing wavelength bands corresponding to channels that have not been selected by the N waveband selectors; the N+1th array demultiplexer being operable to demultiplex the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the non-selected channels. This embodiment allows the demultiplexing of an extra set of channels with an extra array demultiplexer but without the need for an extra wavelength band selector.

In other embodiments, the apparatus further comprises a broadband beam splitter operable to divide the input optical signal into M beams, wherein M is less than or equal to N, M of the N wavelength band selectors being arranged in parallel such that the M beams are routed to the M wavelength band selectors arranged in parallel. Preferably, M is equal to N. A parallel arrangement of the wavelength band selectors allows the loss for each wavelength band selector to be similar. Alternatively, M is less than N, the apparatus being arranged such that N - M wavelength band selectors are arranged in series with at least some of the M wavelength band selectors being arranged in parallel. An arrangement using both parallel and series arrangement of the wavelength band selectors has some of the advantages of these two embodiments and may be the most appropriate arrangement for some applications.

Although it is possible to use fibre gratings connected in parallel or a mixture of fibre gratings connected in parallel and in series as the waveband selector it is preferred to use serially concatenated gratings as this minimises losses due to beam splitting.

In an alternative embodiment, the/each wavelength band selector comprises a multichannel sampled fibre grating.

In accordance with another aspect of the present invention there is provided an optical transmission system comprising a multiplexer for multiplexing a plurality of signals into a single optical signal, a transmitter for transmitting the multiplexed optical signal and a receiver arranged to receive the transmitted multiplexed optical signal the receiver including an optical wavelength division demultiplexing apparatus as described above. This system provides the possibility of sending a large amount of data with a reduced danger of crosstalk between the channels due to the inventive demultiplexer used.

In accordance with a further aspect of the present invention there is provided a method of wavelength division demultiplexing a multiplexed optical signal having a plurality of channels, comprising the steps of: selecting a plurality of wavelength bands corresponding to non-adjacent channels from the optical signal; routing the selected plurality of wavelength bands to an array demultiplexer; the array demultiplexer demultiplexing the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the channels of the multiplexed optical signal.

Embodiments of the present invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Figure 1 illustrates the reflection characteristics of a fibre grating;

Figure 2 illustrates a demultiplexing apparatus according to an embodiment of the invention;

Figure 3 illustrates a series arrangement of a demultiplexing apparatus according to a further embodiment of the invention;

Figure 4 illustrates a parallel arrangement of a demultiplexing apparatus according to a further embodiment of the invention;

Figure 5 schematically illustrates the characteristic outputs of two banks of fibre gratings such as those illustrated in Figure 3 and Figure 4; and

Figure 6 illustrates a transmission system according to an embodiment of the

invention.

With reference to Figure 1, the near-rectangular characteristics of a passband optical fibre grating that was fabricated using an apodised sinc function is shown. A filling factor of F = 0.9 is achievable with the channel separation characteristics provided by this filter response.

For the sake of simplicity, the following embodiments have been described with reference to banks of fibre gratings only. It is however clear that these banks of fibre gratings could be replaced with any wavelength band selectors having suitable filter characteristics. Alternatively, chirped fibre gratings or other gratings that provide a uniform or complex index modulation profile would be suitable.

A demultiplexing apparatus is shown schematically in Figure 2. The device comprises a bank of N/2 fibre gratings 10, an optical circulator 20, and a waveguide array demultiplexer 30.

An input multiplexed optical signal is transmitted via the optical circulator 20 to the bank of gratings 10. The odd-numbered channels from the input multiplexed optical signal are reflected by the gratings 10 back to the optical circulator 20, the remaining signal being transmitted. The optical circulator routes the reflected signal containing the odd-numbered channels to the waveguide array demultiplexer 30. The waveguide array demultiplexer 30 (which may be of the type described in [3]) produces an array of the odd-numbered channels as parallel output signals.

An alternative embodiment dispenses with the circulator 20 and places the waveguide array demultiplexer after the bank of fibre gratings 10. Thus, the waveguide array demultiplexer 30 receives a transmitted beam which comprises the non-reflected channels, in this case the even-numbered channels. The waveguide array demultiplexer outputs a parallel array of the even-numbered channels and the optical circulator is dispensed with.

Alternatively, an additional waveguide array demultiplexer could be used in conjunction with the apparatus illustrated in Figure 2 to provide a parallel array of the transmitted even-numbered channels in addition to the parallel array of the reflected odd-numbered channels. In this embodiment the additional waveguide array demultiplexer

is connected after the bank of fibre gratings to receive the transmitted beam. Thus, a device providing both the odd-numbered channels and the even-numbered channels in parallel would be achieved using this arrangement.

The demultiplexing apparatus illustrated in Figure 2 can be used as a basic building block in more complex demultiplexing systems. A plurality of these multiplexers can, for example, be arranged in series. Figure 3 illustrates an embodiment where two of these devices are connected in series.

With reference to Figure 3, the input multiplexed optical signal is transmitted by the first optical circulator 20 to the first bank of gratings 10, where the odd-numbered channels are reflected back via the optical circulator to a first waveguide array demultiplexer 30. The non-reflected signal, comprising the even-numbered channels, is transmitted to the second optical circulator 21 wherein it is routed to a second bank of fibre gratings 11. The second bank of gratings 11 acts to reflect the even-numbered channels back to the circulator 21 which routes them to a second waveguide array demultiplexer 31. The waveguide array demultiplexer 31 demultiplexes the signal and produces an array of the even-numbered channels in parallel.

The configuration of Figure 3 provides a channel loss of approximately 5dB, related to the circulator and waveguide array, with the bank of even channels exhibiting a 1dB higher loss.

Although the above mentioned embodiment has been described with reference to the use of two banks of fibre gratings adapted to select alternate wavelengths, other embodiments wherein a greater number of fibre gratings, circulators and array demultiplexers with other combinations of channel selection, such as every third, fourth, etc., or alternatively some random selection avoiding adjacent channels, could be chosen.

With reference to Figure 4, an embodiment comprising a parallel connection of two demultiplexers as illustrated in Figure 2 is shown. This embodiment comprises two banks of N/2 fibre gratings 10,11 connected in parallel, two optical circulators 20,21, two waveguide array demultiplexers 30,31 and a 2 x 2 broadband beam-splitter 40.

The input multiplexed optical signal is split into two equal beams by the broadband splitter 40 and the two beams are routed to respective optical circulators

20,21. These optical circulators act to route the beams to respective banks of fibre gratings 10,11 in which the odd-numbered channels from the input multiplexed optical signal are reflected back to optical circulator 20 by fibre grating bank 10 and the even-numbered channels are reflected back to optical circulator 21 by fibre grating bank 11. The optical circulators route the reflected signals to respective waveguide array demultiplexers 30,31 which act to demultiplex the signals and produce respective arrays of odd-numbered and even-numbered channels in parallel.

The parallel connected embodiment has the advantage that each bank of channels has a similar loss. This loss is, however, greater than the series loss, being increased by about 3dB by the 2X2 broadband splitter.

Alternative parallel connected embodiments may comprise a broadband splitter of more than two channels and additional fibre gratings and associated components connected to each channel and operable to reflect ever third, fourth or other non-adjacent wavelength bands. Alternatively, embodiments comprising a mixture of the series and parallel connected embodiments are possible, with some, or all, of the parallel channels containing a plurality of series connected fibre gratings and optical circulators with associated array demultiplexers.

In another parallel connected embodiment, circulators 20,21 are dispensed with and the waveguide array demultiplexers 30,31 are connected after the banks of fibre gratings 10,11 and act to demultiplex the transmitted rather than the reflected channels.

Any of the aforementioned embodiments may be designed as an expandable WDM system, in which initially not all the channel slots are occupied. In the embodiment illustrated in Figure 2, additional expansion of the system is possible by interleaving an additional multiplexer allowing the even-numbered channels to be processed.

Figure 5 illustrates the reflected signals of a bank of fibre gratings such as those illustrated in Figures 3 or 4. These signals form the input to the waveguide array demultiplexers which demultiplex the signals into individual channels corresponding to respective peaks.

With reference to Figure 6, an embodiment of an optical transmission system is schematically illustrated. A multiplexer/transmitter 50 multiplexes data into separate

channels and transmits them as a WDM signal via an optical fibre 40 to a receiver/demultiplexer 60. The receiver/demultiplexer 60 comprises an enhanced demultiplexing apparatus according to an embodiment of the present invention. This demultiplexer demultiplexes the received signal and outputs it as a plurality of separate channels. The separate channels are processed using a data processor 70 or instead to another link or other device (not shown).

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1. Y. Yano et al, ECOC '96 postdeadline paper ThB3.1
2. US-A-5 557 439
3. Z.J. Sun et al, Electronics Letters, pp. 1140-1143, 1997
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5. Smit et al, vol. 2, No. 2, pp. 236 - 250, June 1996
6. Ojha et al, Electronics Letters pp. 78 - 79, 1998

CLAIMS

1. Optical wavelength division demultiplexing apparatus for demultiplexing a multiplexed optical signal having a plurality of channels occupying respective wavelength bands, the apparatus comprising a wavelength band selector and an array demultiplexer connected to receive light from the wavelength band selector;

the wavelength band selector being operable to select a plurality of wavelength bands corresponding to non-adjacent channels from the multiplexed optical signal; and

the array demultiplexer being operable to demultiplex the wavelength bands received from the wavelength band selector to produce an array of output signals in parallel, each output signal representing a respective one of the channels of the multiplexed optical signal.

2. An apparatus according to claim 1, wherein the wavelength band selector is operable to reflect the selected plurality of wavelength bands.

3. An apparatus according to claim 2, further comprising an optical circulator interconnecting the wavelength band selector and the array demultiplexer, a first port of the circulator being arranged to receive an optical signal, a second port being connected to the wavelength band selector and a third port being connected to a waveguide array demultiplexer; wherein the circulator is operable to route the received optical signal to the wavelength band selector and to route the reflected plurality of selected wavelength bands to the array demultiplexer.

4. An apparatus according to claim 2 or claim 3, wherein

the wavelength band selector is operable to transmit remaining components of the input optical signal that have not been reflected, the transmitted signal containing wavelength bands corresponding to the channels that were not selected;

the apparatus further comprising a second array demultiplexer connected to receive transmitted light from the waveband selector;

the second array demultiplexer being operable to demultiplex the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the non-selected channels.

5. An apparatus according to any one of claims 1 to 3, comprising:

N array demultiplexers and N wavelength band selectors, wherein N is an integer greater than 1;

each of the N wavelength band selectors being operable to select a plurality of wavelength bands corresponding to non-adjacent channels from the multiplexed optical signal that are different to the plurality of wavelength bands selected by the other N-1 wavelength band selectors;

the optical wavelength division demultiplexer being arranged such that the selected plurality of bands selected by each of the N wavelength band selectors are routed to a different one of the N array demultiplexers:

the N array demultiplexers being operable to demultiplex the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the channels of the multiplexed optical signal.

6. An apparatus according to claim 5, wherein the N wavelength band selectors are connected in series and are operable to reflect the selected plurality of wavelength bands and to transmit remaining components of the optical signal.

7. An apparatus according to claim 6, further comprising an N+1th array demultiplexer connected to receive transmitted light from the Nth waveband selector containing wavelength bands corresponding to channels that have not been selected by the N waveband selectors;

the N+1th array demultiplexer being operable to demultiplex the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the non-selected channels.

8. An apparatus according to claim 5, further comprising:

a broadband beam splitter operable to divide the input optical signal into M beams, wherein M is less than or equal to N:

M of the N wavelength band selectors being arranged in parallel such that the M beams are routed to the M wavelength band selectors arranged in parallel.

9. An apparatus according to claim 8, wherein M is equal to N.

10. An apparatus according to claim 8, wherein M is less than N. the apparatus being arranged such that N - M wavelength band selectors are arranged in series with at least some of the M wavelength band selectors arranged in parallel.

11. An apparatus according to any one of the preceding claims, wherein the/each wavelength band selector comprises a plurality of fibre gratings connected in series.

12. An apparatus according to any one of claims 1 to 10, wherein the/each wavelength band selector comprises a multichannel sampled fibre grating.

13. An apparatus according to any of the preceding claims, wherein the apparatus is operable to select channels from a multiplexed optical signal comprising nominally equally spaced channels.

14. An apparatus according to claim 13, wherein the wavelength band selector selects wavelength bands corresponding to channels 1, 3, 5, ...

15. An apparatus according to claim 13, wherein R is an integer from 1 to N, and the Rth wavelength band selector selects wavelength bands corresponding to channels R, R+N, R+2N....

16. An optical transmission system comprising a multiplexer for multiplexing a

plurality of signals into a single optical signal, a transmitter for transmitting the multiplexed optical signal and a receiver arranged to receive the transmitted multiplexed optical signal, the receiver including an optical wavelength division demultiplexing apparatus according to any one of the previous claims.

17. An optical transmission system according to claim 16, further comprising an optical fibre link disposed between the transmitter and the receiver.

18. A method of wavelength division demultiplexing a multiplexed optical signal having a plurality of channels, comprising the steps of:

selecting a plurality of wavelength bands corresponding to non-adjacent channels from the optical signal;

routing the selected plurality of wavelength bands to an array demultiplexer; and

the array demultiplexer demultiplexing the received wavelength bands to produce an array of output signals in parallel, each output signal representing a respective one of the channels of the multiplexed optical signal.

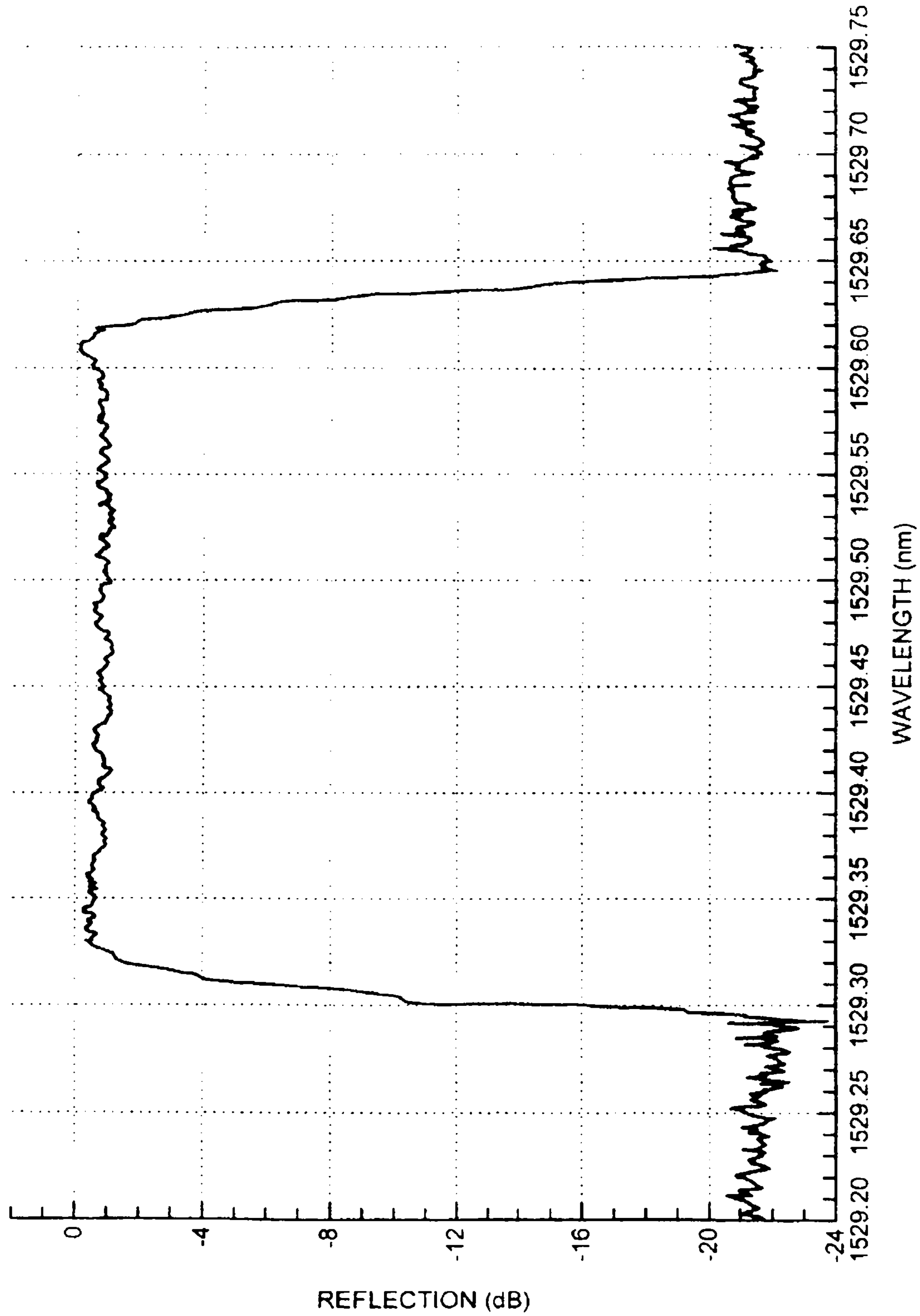
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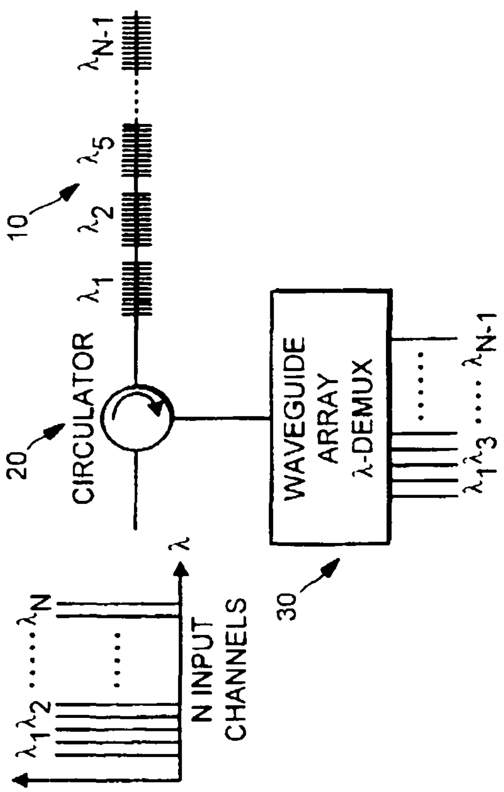
FIG. 1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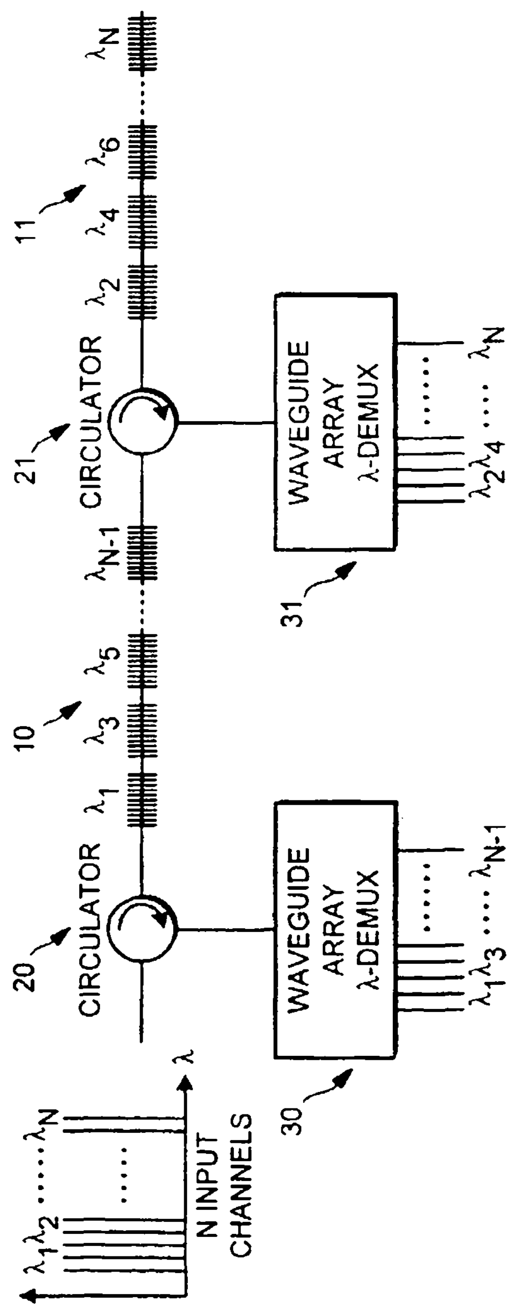
CHANNELS

FIG. 2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λ
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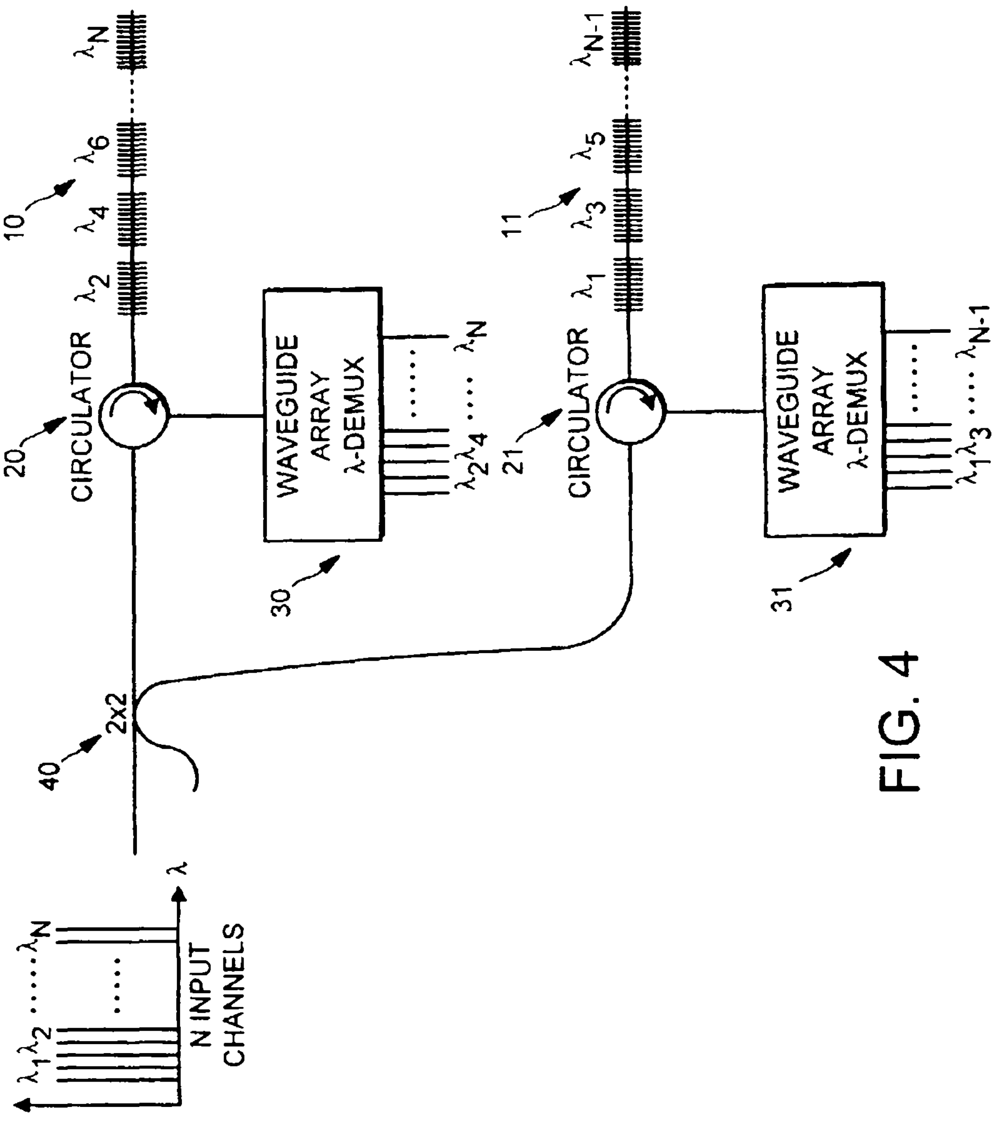
WAVEGUIDE ARRAY λ-DEMUX
10
11
20
21
30
31

FIG. 3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2x2
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λ

FIG. 4

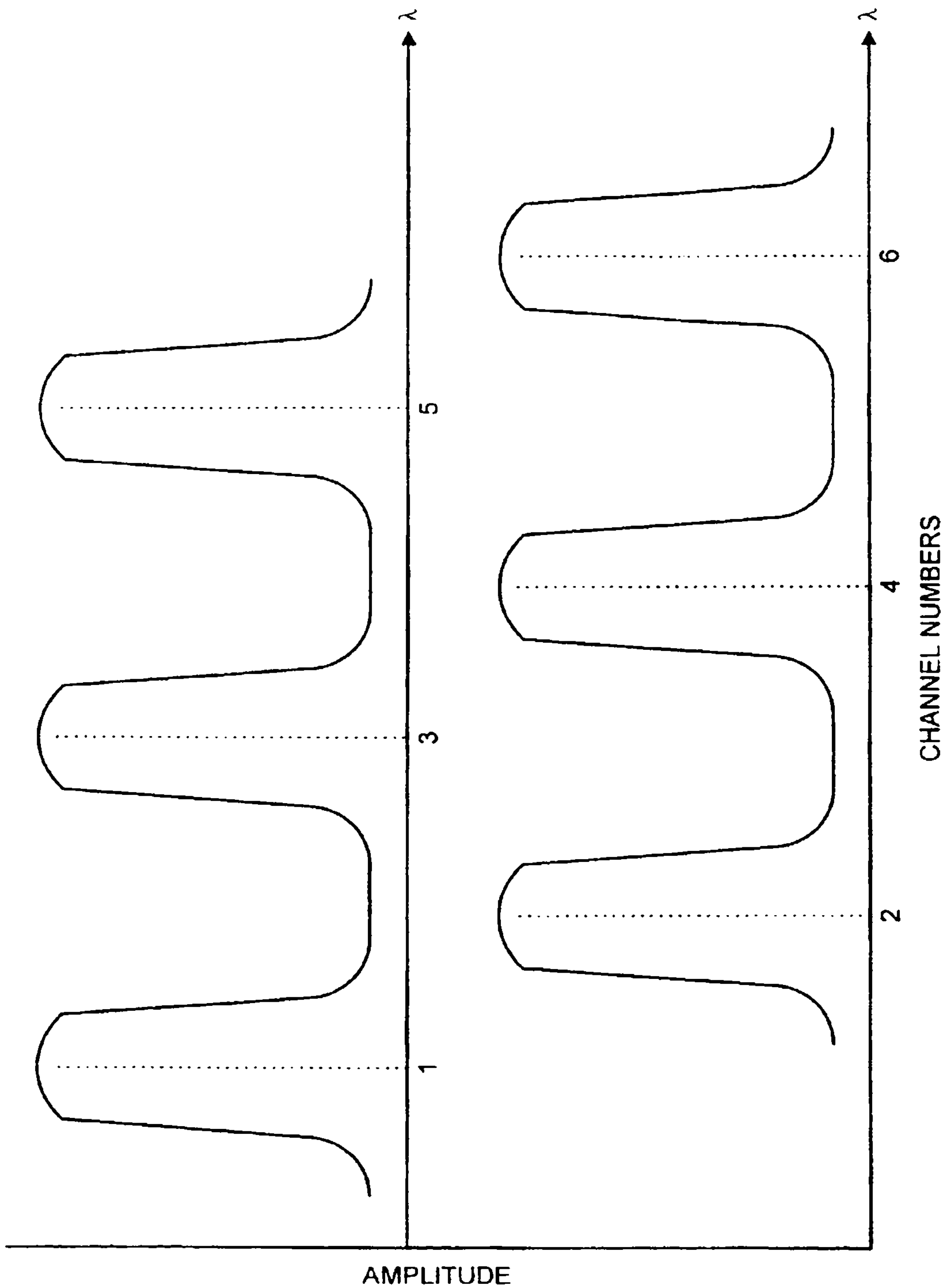

FIG. 5

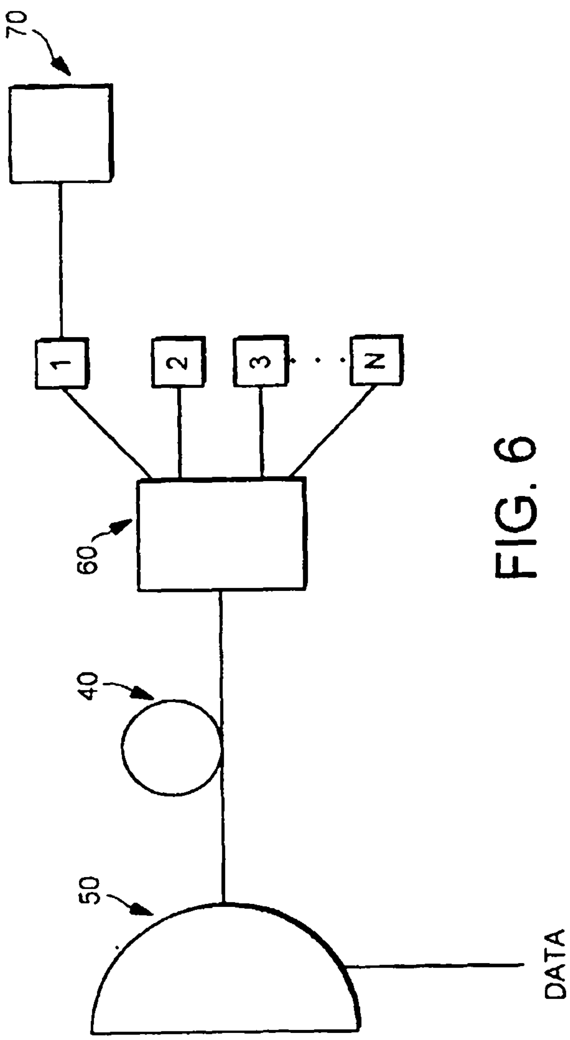

FIG. 6

INTERNATIONAL SEARCH REPORT

International Application No
PCT/GB 98/02254

A. CLASSIFICATION OF SUBJECT MATTER
IPC 6 G02B6/293 G02B6/34 G02B6/12

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC 6 G02B

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practical, search terms used)

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category °	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
X	US 5 457 760 A (MIZRAHI VICTOR) 10 October 1995 see abstract; figure 3 see column 2, line 8 - column 3, line 2 see column 5, line 33 - line 59	1,2,4,5, 7-9, 12-18
A	EP 0 730 172 A (FRANCE TELECOM) 4 September 1996 see abstract; figures 1-5 see column 1, line 31 - column 3, line 47	1,3,6, 8-11, 16-18
A	EP 0 713 110 A (NORTHERN TELECOM LTD) 22 May 1996 see abstract; figure 4 see column 1, line 37 - column 2, line 29 see column 2, line 53 - column 3, line 49	1,16-18

☐ Further documents are listed in the continuation of box C.

☒ Patent family members are listed in annex.

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Date of the actual completion of the international search	Date of mailing of the international search report
3 November 1998	10/11/1998

Name and mailing address of the ISA	Authorized officer
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INTERNATIONAL SEARCH REPORT

Information on patent family members

International Application No
PCT/GB 98/02254

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